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Suitability assessment to establish an industrial park with thermal energy from Chalpatán Geothermal Field, Ecuador

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ABSTRACT

The use of geothermal resources in Ecuador is presently limited to a number of private spas and public recreation centers. In 2020, the total installed capacity for direct heat applications was 5.16 MWt. Preliminary studies commissioned by the Ecuadorian Electric Corporation-CELEC EP were conducted on the Chalpatán geothermal field in 2012. These were executed by the Spanish General Engineering and Survey Company-CGS. Although, initially thought to be a suitable high enthalpy resource for electric power generation, the best scenario obtained from the conceptual model revealed a maximum temperature of 120°C, thus more suitable for direct utilization. Therefore, the field remains under the research scope of the National Institute for Geological and Energy Research - IIGE for possible future direct use purposes.

The province of Carchi, where the Chalpatán geothermal field is located has a great agricultural potential for farmers to practice horticulture, aquaculture, cereal and dairy farming, and livestock rearing. The suitability to establish an industrial park with thermal energy from the Chalpatán geothermal field is the main topic discussed in this paper. The assessment considers a number of factors that include: 1) Possible scenarios for the introduction of low and medium enthalpy geothermal resources into the Ecuadorian industrial matrix, 2) proposed industries for the geo-industrial park, 3) a triple bottom line description of the province where the resource is located, 4) energy supply and demand, 5) equipment sizing and costing, and 6) project profitability.

Two scenarios were considered for the energy supply: 1) Brine from low enthalpy and low-pressure geothermal wells extracted and delivered through heat exchangers and insulated pipes at a distance of 1-2 km, 2) a binary cycle power plant for electricity generation and cascade use of residual heat for direct use purposes. Results of the assessment indicate a favorable scenario for the development of a geo-industrial complex in the area. Moreover, the province where the resource is located would greatly benefit from the utilization of low and medium grade geothermal heat. Nonetheless, the role of the government in securing proper funding for an exploratory drilling operation to confirm the geothermal reservoir remains crucial.

1. INTRODUCTION

Chalpatán geothermal prospect is located in Carchi, which is one of the northest provinces of Ecuador and shares the border with Colombia. It is the third most important in the economy of Ecuador behind Guayas and Pichincha, and generates important income from import and export trade. The province has six cantons but only the canton of Tulcán has access to the commercial exchange border with the Department of Nariño, which takes place officially through the Rumichaca international bridge. It has a fundamental strategic importance as it offers a great opportunity for economic and social development of the province. The official activity is very wide-ranging: agricultural products, textiles, livestock, dairy products, sorted merchandise and others. Currency exchange is also a profitable activity that benefits a large number of inhabitants (GAD-Carchi, 2015).

Figure 1: Administrative map of Carchi

Its mountainous nature, with soft valleys of fertile soils of volcanic and glacial origin, provides the province of Carchi with a good agricultural potential. An important dairy industry has been established over the past decades in the province, as well as potato crops which represent 38% of total national production according to the agricultural public information system SIPA (2019). In addition to potato and milk production, other agricultural products such as beans (in the hot and warm dry area) and certain fruit trees typical of the warm dry and subtropical areas Northwest and Southwest of the province stand out with 15% share of the total national production. Nonetheless, the most important quantitative change has been the presence of the flower production industry in moorlands, which began in 1997 and has been increasing over the years.

According to the results obtained from the Survey of Agricultural Area and Production for the year 2017 in the province of Carchi, mountains and forests are predominant in the area, followed by cultivated and natural pastures. Consequently, timber harvesting and logging as well as production of pasture for dairy cattle are among the most common activities. Extraction of mineral, energy and water resources is also seen although not in a major scale. A minor but not negligible area for recreational, cultural and scientific purposes closes the total distribution of land use in the province.

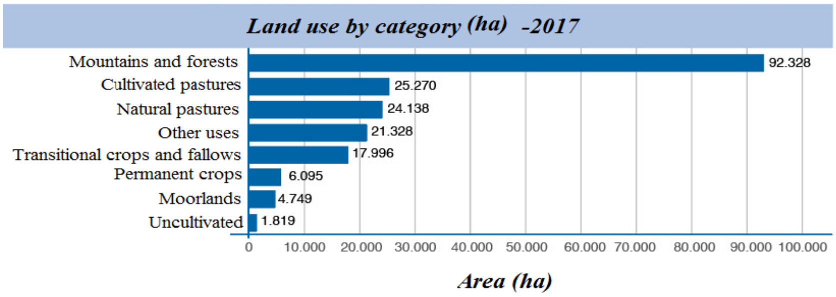

Figure 2: Land use by category in the province of Carchi

The economically active population (PEA) is employed in agriculture (47%), services (32%), industry (12%) and the percentage of unemployment is approximately 9%. For this reason, the agricultural, commercial and transport sectors are the ones in which the province has the highest levels of competition and productivity. The Commerce and Services sectors are mostly concentrated in its capital (Tulcán) (GAD-Carchi, 2015).

According to the province´s Development and Territorial Distribution Plan (PDOT), despite being Ecuador´s third most important province in terms of revenue income to the state, Carchi contributes only 0.68% to the National Added Gross Value (VAB) production index. This marginal contribution is mainly related to primary goods being produced with almost no added value (GAD-Carchi, 2015). Moreover, there is not a robust infrastructure that can fully support the development of the mentioned resource's potential that the province has, especially in the means of industrial and agriculture-industrial capabilities, as well as other technological advancements. Another impediment to industrial development in the province has been the high cost of fuels, among the most relevant being diesel, LPG and furnace oil, which are normally used to fire boilers. Since 2012, subsidies to these fuels, granted for approximately 20 years, were removed from the industrial sector decreasing the margins for profit in the industries that require steam for their operations. On the other hand, the use of greenhouses in the province is limited due that research, training, and advertisement of technology to increase productivity in agricultural crops is limited. This has caused most farmers to maintain empirical practices in open field crops. As a result, the changes in the productive yield per hectare vary each year depending on climate factors, such as the lack or excess of rain, and environmental temperatures outside the optimal growth range of the crops (INEC, 2011). Altogether, these factors are well known by the local authorities, and have been taken into account in the definition of strategies towards the development of the province's economic, social and environmental short term goals.

2. CHALPATÁN GEOTHERMAL RESOURCE

The Chalpatán geothermal resource is a Late Pliocene – Early Pleistocene andesitic to silicic collapse caldera 8 km in diameter, located 20 km SW of Tulcán. The structure originated from the collapse of the roof from a shallow magma chamber, which occurred between 2 and 1.2 Ma, according to two indirect absolute dates carried out in 1987 (Beate & Salgado, 2005). This geothermal resource is located in a benign environmental and social area of approximately 132 km^2 at an average elevation of 3200 m.a.s.l (Beate & Urquizo, 2015).

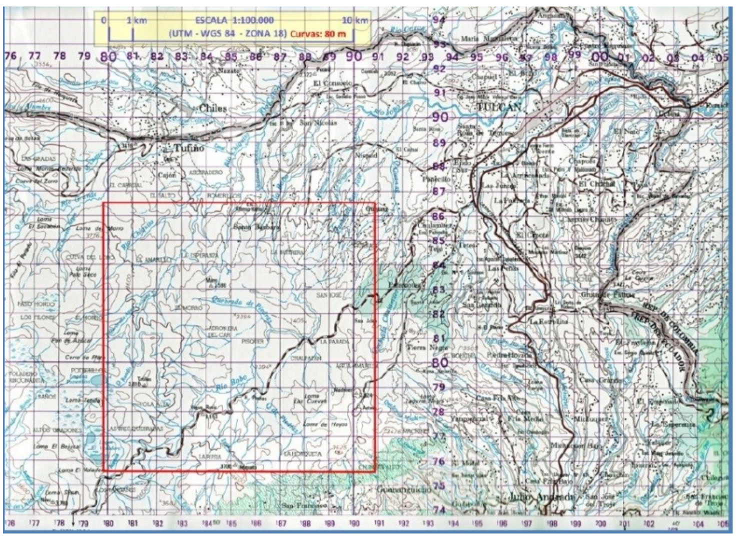

Figure 3: Location of the geothermal area of study-Chalpatán (CGS, 2013)

As indicated by Beate and Urquizo (2015), the caldera floor is cut by a NNW-SSE fault and the basement at the eastern block is uplifted as compared to the western block. Regional NNE faulting affects the caldera and has associated normal faults. Caldera fill is complex and consists of pyroclastic deposits, sediments and lavas, which are less compacted down to 1000 m, but the compaction increases towards caldera floor at 1600 m. The infill lavas reach a thickness of 500 m and are covered by a 10 to 80 m thick impermeable cover of volcanic ash and till.

The Chalpatán Caldera was briefly studied between 1981-1982 and again in 1986-1987 as the result of the Binational project Tufiño-Chiles-Cerro Negro, between the governments of Ecuador and Colombia (Lloret & Labus, 2014). With this baseline information, advanced reconnaissance studies, which included geochemical sampling, satellite and infrared thermal scan, deep electrical tomography, Audio-MT, MT and airborne magnetometry were conducted in 2012 by the Spanish General Engineering and Survey Company-CGS. Although initially thought to be a high enthalpy resource, after appraisal studies ended in 2013, the best scenario obtained from the conceptual model revealed a maximum temperature of 120ºC (CGS, 2013). Despite the fact that it would still be possible to generate electricity through a binary cycle plant (Verkís, 2014), additional findings from the CGS study indicate the presence of an estimated hot water reservoir of 1850hm^3. Therefore, this geothermal prospect is undoubtedly more suitable for direct use purposes.

3. POSSIBLE SCENARIOS FOR THE INTRODUCTION OF LOW AND MEDIUM ENTHALPY GEOTHERMAL RESOURCES INTO THE ECUADORIAN INDUSTRIAL MATRIX

Five scenarios, based in the level of integration of industries into the geothermal park between the years 2020 and 2035, were simulated by (Fontalvo, 2020). The forecast was done using the Long-range Energy Alternatives Planning –LEAP software. Among the sources of information that were used to elaborated these projections, are statistics from industry and energy sector, as well as Nation and Province GDP indicators. The five scenarios are detailed in the following table:

Scenario	Temperature (ºC)	Description
1. Business as usual (BAU)	--	No use of geothermal resources
2. Low enthalpy geothermal (IGB)	70-90	Horticulture, aquaculture, crop drying, recreation.
3. Medium enthalpy geothermal (IGM)	70-100	IGB+ Milk Processing, textile manufacture
4. Industrial Park Geothermal (PI)	70-110	IGM+ leather treatment, paper production
5. Power Plant Geothermal (CE)	70-120	PI+ Electricity generation

Table 2: Scenarios for the introduction of geothermal resources into the Ecuadorian industrial matrix. (Fontalvo, 2020).

Of the analyzed scenarios, the Low Enthalpy Geothermal (IGB) can be considered as of high interest for a first step of direct geothermal application, given the lower initial capital requirement. However, it should be noted that the Medium Enthalpy Geothermal (GM) scenario presents a lower cost in the total life of the project and a greater reduction in emissions than the IGB scenario; therefore it is of greater benefit in the long term and would be the recommended if the necessary resource exists. The Industrial Park (PI) and Power Plant (CE) scenarios are more speculative, since they depend on a higher temperature in the reservoir, as well as on higher economic investments. However these scenarios add a component of industrial diversification in a region eminently commercial and agricultural.

4. SUITABILITY OF CHALPATÁN FOR INDUSTRIAL DEVELOPMENT

The area surrounding Chalpatán geothermal field is of great agricultural potential. The province has productive circuits for potatoes, milk and meat. Additional productive chains have also been identified, among them coffee, fruit trees, tourism and beans. The establishment of agro-processing industries around Chalpatán geothermal field will provide nearby farmers with the opportunity to supply the industries with raw materials for production. In addition, this medium-low enthalpy resource is located within a short distance of Tulcán, the capital of Carchi. Although a fairly good amount of goods produced by the Geo-Industrial complex will be consumed by the city of Tulcán and three colliding provinces, most of the production will serve as trade-offs with Colombia through its nearby border city of Ipiales. This is in line with the local government which has put in place a proposal to overcome the low level of agro-industrial development. The proposal consists of adding value to local goods through the development of sectors that are sensitive for the local economy (CGS, 2013).

4.1 Land use availability

The entire interior of the Chalpatán caldera is covered by scrub, generally with a low vegetation density. The forest mass is reduced to a few small areas in the North and East of the circular structure. The inhabitants in the surroundings of the Chalpatán caldera (between the Espejo and Tulcán cantons) carry out activities related to agriculture, livestock, forestry and fishing. All agricultural activity is located outside the volcanic structure and the surrounding area.

Figure 4: Panoramic view of Chalpatán caldera (CGS, 2013)

4.2 Availability of energy

The Chalpatán geothermal prospect stores a large thermal resource, which can be economically exploited for industrial use near the edges of the caldera. The proximity of the prospect to the electric transmission lines will allow supplying energy to all the industries located in the area of influence if the resource is exploited only for direct use purposes. If, on the contrary, a decentralized electricity generation through the construction of a binary cycle plant is considered, the industrial park will be self-sufficient and the surplus will be able to feed the National Interconnected System (SNI).

4.3 Availability of raw materials

Carchi has 193,700 hectares of land in use, which represents 2% of the total land in the country, dedicated to horticulture. In this province there is an important production of potatoes, vegetables, cereals and livestock, mainly milk, in addition to the existence of protected areas that are an important for tourism (GAD-Carchi, 2015). Consequently, the Chalpatán geothermal prospect is surrounded by a resource-rich area. This area, which includes the cantons of Espejo, Tulcán and San Isidro, produces a significant amount of raw material and resources that can supply the industries that are installed in the surroundings of the Geo-industrial complex.

4.4 Availability of education

Qualified personnel with at least a bachelor´s degree from high education centers and universities can be readily available to work in the industrial park. Among the main universities that exist in the province are: the Carchi State Polytechnic University, the Regional Autonomous University of the Andes, the Higher Technological Institute, and others. New industries set up in the area of influence will benefit from trained technical and administrative personnel. In addition, other specialized educational centers located in the province of Imbabura, such as Yachay Tech, will also contribute to the development of new technologies and manufacturing processes.

4.5 Availability of Housing

The highest concentration of housing units is found in the city of Tulcán. As it is the most developed and close to the area of influence of the geothermal prospect, it can accommodate the demand for housing that is generated as a result of industrial development. Small nearby towns can also be considered within the available housing offer.

4.6 Availability of access roads and transport services

The geothermal prospect is accessible through a minor district road that connects to the Pan-American Highway, which is a national transport route for industrial goods. It can also be reached from the city of Tulcán or from the city of Ibarra via the El Ángel Ecological Reserve. There are public transport services available that reach the location of the proposed geo-industrial complex.

4.7 Availability of hospitals

First-line Hospitals are located in the cities of Tulcán and Ibarra which are approximately 40-60 minutes from the proposed location of the project. These Hospitals are both public and private. There are also a number of clinics nearby that can provide first aid care in case of minor injuries.

5. PROPOSED INDUSTRIES FOR THE CHALPATÁN GEO-INDUSTRIAL PARK

The predominance of agricultural activities in the province of Carchi suggests that the main industry is based mainly on the development of the agro-industrial sector. However, other non-related industries that are compatible with the use of the medium and low temperature geothermal resource might as well be part of the geo-industrial park. Based on the information contained in the PDOT of the Province of Carchi (2015), core industries have been identified as potential users of the geo-industrial park. Some of the most relevant in terms of opportunity and relevance to the province are discussed below.

5.1 Horticulture

Horticulture comprises the production of fruits, vegetables, and flowers. In the province of Carchi there is a great diversity of crops. Based on the results obtained in 2019 from the Ecuadorian Agricultural Statistics (ESPAC), the total area used for cultivation reaches 17403 Hectares. In the following table, we see the different types of crops based on this referred classification are depicted in the following Figure.

MAIN CROPS-2019
Province: Carchi

N°	Crops	Cropped area (ha)	Cultivated area (ha)	Production (ton)	Yield (ton/ha)
1	Potato	6.145	6.145	196.737	32,01
2	Barley	2.176	2.176	5.722	2,63
3	Baby green pea	2.149	2.092	8.619	4,12
4	Fava bean	1.966	1.833	9.074	4,95
5	Wheat	1.921	1.577	1.417	0,90
6	Banana	902	902	2.282	2,53
7	Corn (soft)	840	610	2.788	4,57
8	Corn (dried seed)	349	343	1.782	5,20
9	Tomate	319	280	428	1,53
10	Baby bean	242	242	10.692	44,19
11	White Onion	233	233	1.232	5,30
12	Sugar Cane (for sugar)	194	194	829	4,27
13	Sugar Cane (other uses)	179	48	4.389	90,91
14	Dried pea	158	135	4.280	31,80
15	Mango	147	141	99	0,70
16	Coffee	146	58	296	5,10
17	Quinoa	97	97	46	0,47
18	Cacao	69	69	197	2,88
19	Dried fava bean	57	57	45	0,79
20	Tree Tomato	51	43	142	3,35
21	Dried bean	49	48	1.319	27,60

Figure 5: List of main crops arrange by cropped and cultivated area

Potato is the most cultivated root vegetable in the Province and represents 38% of the total production in the country. Other high value crops for the domestic market such as beans, corn and tomatoes, also stand out.

While most farmers practice open field horticulture, there is a growing interest in Ecuador to invest in greenhouse farming in order to overcome unpredictable weather patterns that affect the productivity of crops. On the other hand, the use of indoor climate control to increase productivity and reduce maturity time is also seen as a competitive strategy among the flower export industry. However, the high cost of fuels to regulate humidity and temperature inside greenhouses shadows the potential benefits that can be obtained.

Geothermal water at 55ºC can be used to provide thermal energy to heat greenhouses in the surroundings of the Chalpatán Caldera. Moreover, hot water at 100ºC can also provide energy for cold storage using Lithium Bromide vapor absorption refrigeration systems (Kiruja, 2017). This is especially useful for medium and large scale farmers using greenhouses to grow flowers.

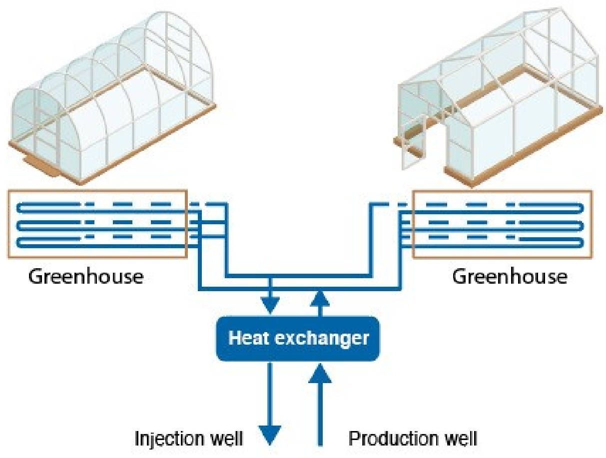

Figure 6: Greenhouses geothermal heating system layout

5.2 Aquaculture

The inter-Andean region of Ecuador has ideal freshwater sources for developing fish farming activities, allowing the diversification of marine species and improving production volumes. The fish farming industry is trending in the country with great potential in the production of alternative foods of high nutritional quality.

The main species of freshwater fish farmed in Ecuador (besides shrimp aquaculture) are Tilapia and Trout. Ecuador is ranked 5th in the top Tilapia producers in the Americas, with a volume of 23000 Metric Tons (MT) (FAO, 2020). The production of hatchery trout differs depending on the country`s region. The North region produces 512 MT, while the Center and South regions produce

218 MT and 252 MT respectively. 209 hatcheries exist according to production statistics of the Ministry of Agriculture, Livestock, Aquaculture and Fisheries, of which 92% are actively operating. Nonetheless, other promising species which can be adapted for fish farming in climates with characteristics similar to the Chalpatán region are the Piracuru, also called arapaima or Paiche, Cachama fish, Bocachico, Tarpon, Catfish, Tiger Shrimp, and Carp.

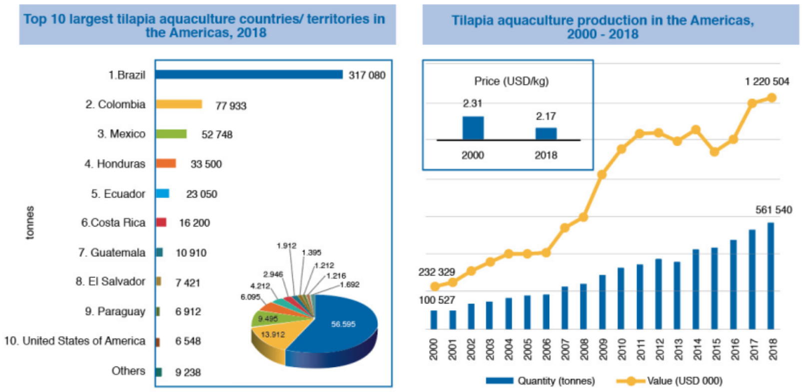

Figure 7: Tilapia aquaculture production in the Americas (FAO, 2020)

The potential of geothermal energy in aquaculture may be greater than in animal husbandry, such as pig and chicken rearing. One of the benefits of geothermal fisheries is the possibility that fish can grow in a more controlled environment with regulated water temperature and PH, among other parameters related to health and growth. Therefore, fish are healthier and stronger than if they were grown in unheated ponds. Fish farmers can regulate temperature throughout the year to make sure the fish grow to a consistent size year-round. Tilapia and catfish grow best in ponds with temperatures approaching 30ºC. Trout however, require a lower temperature for optimal growth, which is half of what it is required for Tilapia (Boyd & Lund, 2006). Approximately 0.95 kg/s of heated water will maintain a geothermal pond within the 30ºC range limit (Kiruja, 2017).

An interesting cascade circuit can be set between horticulture and aquaculture in order to maximize the benefits of using geothermal energy. For example, the water that flows out of a geothermal fish pond can be used as an irrigation source for nearby greenhouses within the geothermal park.

5.3 Milk Processing

In Ecuador, 55’579 975 liters of milk were consumed in 2019 according to the statistics from the Ministry of Agriculture and Livestock (MAG). Approximately 8% of the total was produced in Carchi, where an important dairy industry exists in the cantons of Montufar, Huaca, Tulcán and Espejo. Consequently, it constitutes one of the most important activities for job creation and added value in the Province (GAD-Carchi, 2015). The dairy industrial sector in the country moved approximately USD 1400 million per year due to the production and industrialization of milk (Gallegos, 2019).

Of the approximately 6’000 000 liters of milk produced in the country per day, 50% goes to the dairy industry where is processed into pasteurized skimmed milk, powder milk, cheese and yogurt; 20% stays on farms for self-consumption, while the remaining 30% goes to the informal market as raw milk. Among the proposals to reduce informality the dairy industrial sector is evaluating reaching other markets, such as Panamá and Perú, where production does not supply the current demand.

Almost all of the dairy products and milk derivatives can be readily processed using thermal energy from wells located in the geothermal park. The thermal energy requirements for milk processing are shown in Table 2.

Process	Energy Usage (KWth/liter)	Temperature (ºC)
Low temperature short time pasteurization	0.056	100
Milk cultures processing	0.35	130
Milk sterilization (UHT)	0.35	130
Powder milk, cheese making	0.5	200

Table 2: The thermal energy requirements for milk processing (Kiruja, 2017).

5.4 Pulp and paper production

Paper and cardboard production in Ecuador comprise a wide range, from office use and school supplies, to boxes, sacks, books, toilet paper, napkins, among others. Paper bags and cartons are also manufactured to supply industrial storage needs.

Pulp making for paper production can be done mechanically or chemically. The pulp is then bleached and further processed, depending on the type and grade of paper that is to be produced. In a paper factory, the pulp is dried and pressed to produce paper sheets (Bajpai, 2015). Chemical or mechanical pulp is not significantly produced in the Province, nor anywhere else in the country to obtain paper. At present, the raw material is mostly obtained from imports. In a minor scale pulp is locally generated as a by-product of bagasse and paper recycling activities. Between January and November 2018, imports of raw materials, intermediate and final products of paper and cardboard totaled USD 377 million. On the other hand, the country exports final products derived from paper and cardboard, being the main destination Colombia (37%) and Peru (20%).

Consequently, stablishing and paper industry in the geothermal park has the potential of enhancing export volumes with Colombia while reducing distance and operating costs considerably. The energy requirements for pulp and paper processing are shown in Table 3.

Process	Vapor requirement (GJ/Ton)	Electricity Requirement (kWh/ton)	Temperature ºC
Chemical Pulp	Optimum= 10 Medium= 16 High= 22	Optimum= 600 Medium= 800 High=1000	120
Mechanical Pulp	Optimum< 10 Medium= 4 High= 8	Optimum= 2500 Medium= 2800 High= 3400	--

Table 3: Energy requirements for pulp and paper processing (Suárez, 2016)

5.5 Tourism

The relationship between geothermal energy and tourism industry is evident. This energy has been most often used in spas, for healing treatments, recreational purposes and for the heating of facilities. Examples of practical applications can be found in projects such as "The Blue Lagoon" in Iceland or the "Olkaria Geothermal Spa" in Kenya.

A top class resort or spa located in the Chalpatán caldera would certainly be of interest for national and international tourists. A heat exchanger with brine from low enthalpy and low pressure geothermal wells would provide enough amount of warm water for heating, bathing and other ancillary water services. Another advantage is that the resource collides with El Angel, a natural reserve that can also be exploited in terms of ecological tourism. Geothermal analyses indicate the presence of sodium-calcium bicarbonate waters with an appreciable amount of SiO_2 (CGS, 2013). These elements might be worthy of exploitation for healing purposes.

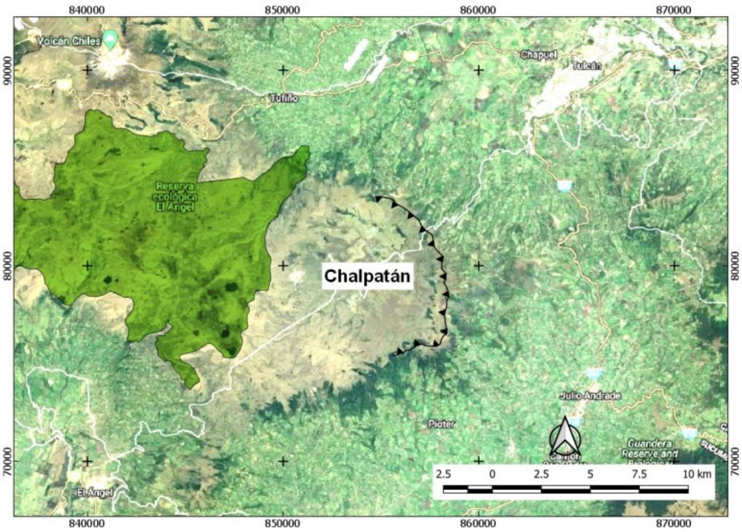

Figure 8: Location of the Chalpatán caldera next to the "El Angel ecological reserve"

6. ENERGY SUPPLY AND DEMAND IN CHALPATÁN INDUSTRIAL PARK

The energy supply and demand for the Chalpatán industrial park was estimated based in thermal energy potential, which was obtained from the preliminary studies carried by CGS in 2012, and the thermal energy requirements for each of the industries discussed in the previous section. It is worth noticing that a conservative scenario using a pessimistic hypothesis was considered. If on the contrary, appraisal well drillings, which are still to be carried out in the field, confirm the best possible results, then the amount of energy available would double the current base scenario.

6.1 Energy Availability

Based in the results from the mathematical model under a steady state status, derived from the prefeasibility studies in 2012 (Table 4), the large amount of thermal energy, which is mostly stored in the rock, indicates that there is a great heat source underneath the Chalpatán Caldera.

Unit	Stored in rock	Stored in water	Total Energy
Joules	$1.637x10^{18}$	$1.055x10^{17}$	$1.742x10^{18}$
GWh	454 722	29 167	483 889
Kcal	$3.91x10^{14}$	$2.52x10^{13}$	$4.16x10^{14}$
Tonnes of oil equivalent (toe)	39'097 126	2'507 757	41'604 883
%	94	6	100

Table 4: Stored energy in the Chalpatán geothermal prospect (CGS, 2013)

A deep Electrical Tomography combined with Magnetotellurics, among other geophysical studies, were undertaken in Chalpatán to have a better understanding of the underground profile. The low resistivity values observed in the caldera infills suggest that this level is saturated with water, presumably hot, and that it must have a notable percentage of water content. A cross section of the Caldera is observed in Figure 9

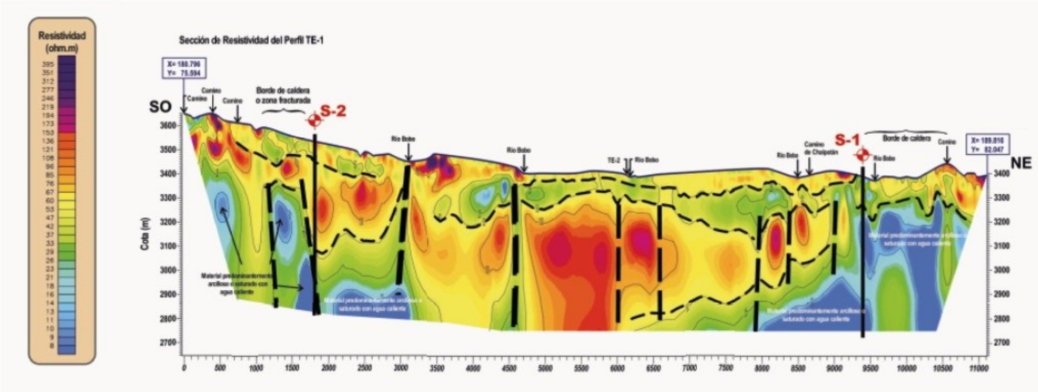

Figure 9: Resistivity cross section of the Chalpatán Caldera (CGS, 2013)

Basal temperatures in the Chalpatán caldera are estimated to be between 70º and 120 ºC depending on the degree of thermal evolution in which the system is currently at. The estimated volume of hot water (1,850 hm^3 at a temperature of 70ºC in the pessimistic hypothesis, equivalent to 484,000 GWh of thermal energy) constitutes an enormous energy resource that can be exploited for direct use purposes. The volumetric capacity of the geothermal resource is shown in the following Table 5:

Structure	Total Volume (km^3)	Volume x ΔT Weighted	Volume of water at 70ºC (km^3)
Fine reworked volcanoclastic and tuffs	9,70	-	-
Lava flows	2,23	-	-
Caldera Infill	61,89	853,24	1,85

Table 5: Volumetric capacity of the geothermal resource (CGS, 2013)

6.2 Energy extraction

Two drilling targets were proposed by CGS in the prefeasibility study´s final report. These are meant to intersect the faults, located in the edges of the Caldera at a depth of 1500 m. Figure 10 shows the locations of the drilling targets, marked as S-1 and S-2.

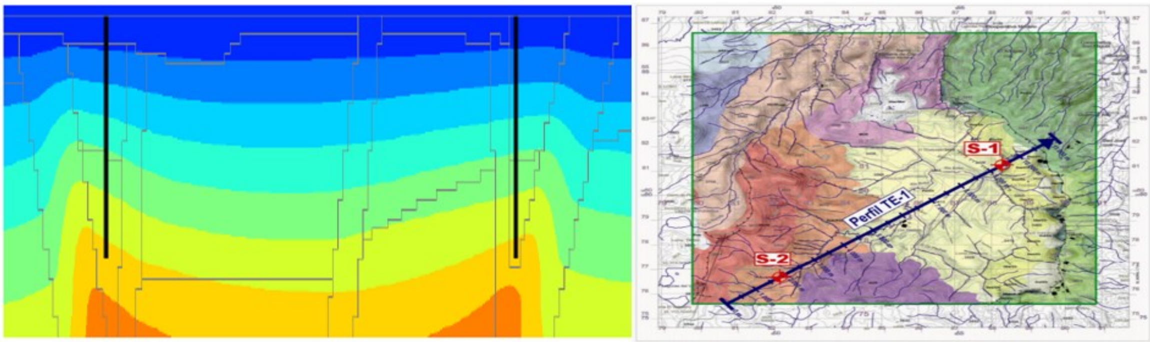

Figure 10: Locations of the drilling targets in the caldera (CGS, 2013)

6.3 Cascade utilization of geothermal resources

All of the key industries described in the previous section can be set up in the Geoindustrial Park; some processes have high temperature requirements while others have lower requirements. In order to make the exchange of energy among these processes most efficient while reducing thermal losses, the concept of cascade energy comes into play. The harnessing of geothermal heat at different thermal levels in sequential processes. This can include the production of electricity at a minimum threshold temperature using ORC Technologies, or a cascade system comprising only thermal uses. In either case, the correct sequence of industries that result in better energy utilization must be carefully planned (Rubio-Maya et al., 2015).

Figure 11 shows an example of the thermal levels in sequential processes that can be implemented in Chalpatán, based on the estimated temperature of the geothermal resource:

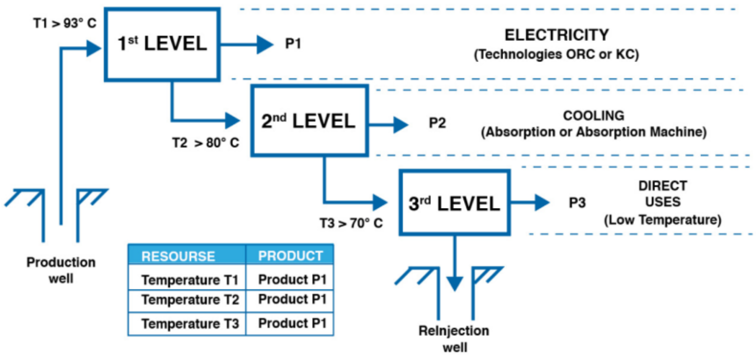

Figure 11: Conceptual diagram of the cascade utilization of geothermal energy (Rubio-Maya et al., 2015)

6.4 Energy demand

The energy requirements for some of the industries considered in the previous section are shown in Table 6:

Industry	Process	Thermal energy requirement	Inlet temp. (°C)	Outlet temp. (°C)	Thermal energy consumption (kJ/s)
Greenhouse	Greenhouse heating	300/1000 kWth/ha	55	40	467
Aquaculture	Aquaculture heating	1,260 kWth/ha	40	-	245
Milk Processing	Milk pasteurization	0.056 kWth/liter	100	90	788
Textile	Chemical processes	10 kg of hot water/kg of fabric	100	-	38
Recreation	Water heating	180 kWth/kg of water	40	-	833
Water Treatment	Water heating		80	65	616
				Total	2987

Table 6: Energy requirements from potential industries of the geo-industrial complex adapted from (Kiruja, 2017)

Since no wells have been drilled at the time of publication of this document, no data regarding flow rate is available. Therefore, the size/area for the proposed industries would be determined according to the supply of hot water, dictated by the pressure of future wells drilled onsite. Estimated flow rates for a specific area of land to be utilized by selected industries are shown in Table 7:

Industry	Process	Area (ha)	Mas flow rate (Kg/s)	Temperature (ºC)
Horticulture	Greenhouse heating	10	7.41	55
Aquaculture	Pond heating at 29ºC	4.7	4.44	40
Dairy	Pasteurization (250.000 litres/day)	-	18.75	100
Recreation	Pool heating (1m depth)	0.2	4.63	50-70
Maintenance	Cleaning/Washing	-	-	80
	Total	14.9	35.23	100*

* The average temperature for the highest energy intensive process is considered

Table 7: Energy demand per process adapted from (Kiruja, 2017)

7. EQUIPMENT SIZING AND COSTING

Equipment Sizing and costing was elaborated based in the following scenarios:

- Scenario 1. Brine from low enthalpy and low-pressure geothermal wells extracted and delivered through heat exchangers and insulated pipes at a distance of 1-2 km,
- Scenario 2. A binary cycle power plant for electricity generation and cascade use of residual heat for direct use purposes.

7.1 Scenario 1

The equipment required for the direct use of medium and low enthalpy geothermal resources in the geo-industrial park, mainly involves the use of pumping elements and heat exchangers; a main pipeline, a return pipeline and a reinjection pipeline with proper expansion loops to prevent thermal expansion; and, the use of adequate insulating materials to reduce thermal losses. A schematic diagram for a proposed layout based in a direct use only configuration is shown below:

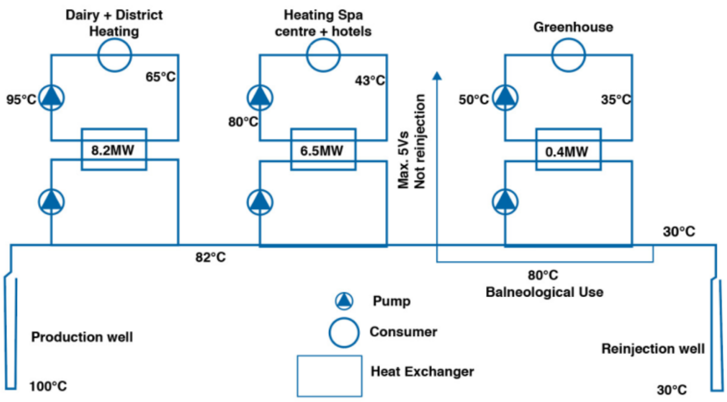

Figure 12: Schematic diagram for direct use purposes (Rubio-Maya et al., 2015)

Based in the previous diagram, the following elements are sized accordingly in the following Table 8

Source of thermal Energy	Available energy (MW)	LMTD (ºC)	Heat exchanger area (m^2)
Low pressure well	8.2	48.5	25.6
	6.5	41.9	23.5
	0.4	17.4	3.48

Table 8: Heat exchanger area

The pipeline system was assumed to be composed of the following sections:

1. Main pipeline, which carries fresh hot water from the heat exchanger to the industrial park.
2. Return water pipeline, which carries the recirculating water from the industrial park to the heat exchanger.
3. Brine reinjection pipeline, which carries brine from the production well to the reinjection well across the heat exchanger.

Since the precise location for the industrial park is not known, some elements were sized based on topographical conditions, as well as other assumptions such as high pressure loss, pump head, flow rate and highest net present value of a project with similar characteristics, which were recommended by (Kiruja, 2017). These calculations are for reference purposes only and will need to be adjusted once more details of the project become available.

7.1.1 Pump sizing

The pumps selected for this scenario are shown in Table 9:

Number of pumps	Main pump		Return pump	
	Pump head (m)	Power rating	Pump head (m)	Power rating
3	70	23 kW	90	6kW

Table 9: Pumping requirements

No pump was considered for reinjection due that a downhill flow was assumed.

7.1.2 Pipeline sizing

To properly size the pipeline system for direct utilization, external parameters corresponding to mean air temperature, air density and geothermal brine temperature at the production well were considered and they are shown in the following Table 10:

Location	Mean air temperature (ºC)	Air density (kg/m^3)	Geothermal brine temperature (ºC)
Chalpatán	7	0.85	100

Table 10: Pipeline sizing parameters

The following thermodynamic properties for air and water were also considered and are shown in the Table 11 below:

Thermodynamic properties	Fluid	
	Water	Air
Specific heat *Cp (J/KgºC)*	4186	1006
Density ρ (Kg/m^3)	1000	0.85
Dynamic Viscosity μ (Kg/ms)	2.82x10^{-4}	1.78x10^{-5}

Table 11: Thermodynamic properties for air and water

The pipeline has the following external and internal diameters, shown in Table 12 and depicted in Figure 13:

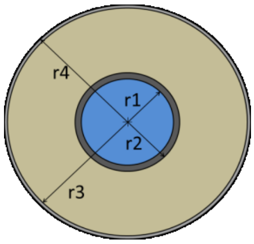

Figure 13: Cross section of insulated pipeline

Radius	Size (mm)	Element	K(#)	K (W/mºC)
r4	200	Air	5	0.02
r4 – r3	3	Aluminum	4	205
r3 – r2	50	Rockwool	3	0.44
r2 – r1	0.6	Steel	2	54
r1	150	Water	1	0.58

Table 12: Pipeline external and internal size

Figure 13 shows the materials and inner elements that are present in the design of the pipeline. The outer shell between r4-r3 is made of aluminum and holds the insulating material (rockwool) that surrounds the inner carbon steel pipe between r3-r2. Hot water circulates through r1 with minimal thermal losses as the result of insulation properties of the rockwool. The theorical temperature drop calculation along an insulated 20 km pipeline was done based on Newton's law of cooling and the data form the location of the Chalpatán geothermal resource (Jijón, 2019). Results are shown in Figure 14

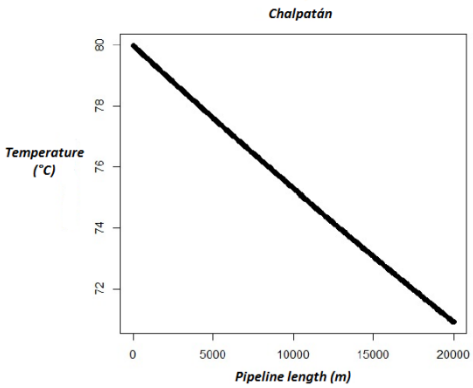

Figure 14: Temperature drop along the pipeline

7.2 Scenario 2

If production of electricity is taken into consideration, the addition of a binary cycle plant that use the Organic Rankine Cycle (ORC) technology is commonly the best option in this type of low enthalpy reservoirs. A diagram of a single stage Binary cycle plant is showed in Figure 15:

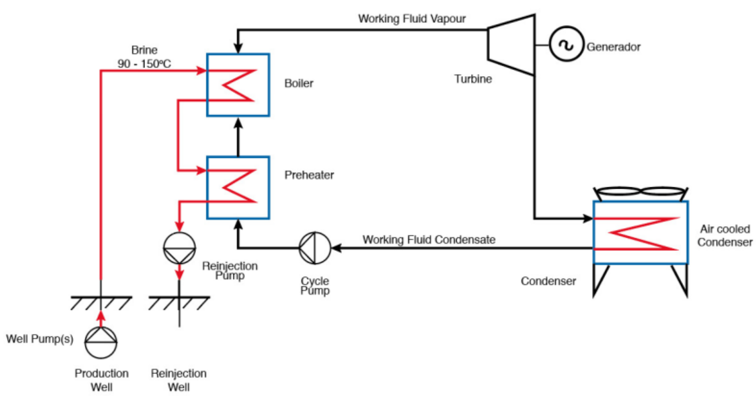

Figure 15: Diagram for one-stage binary cycle plant proposal (Verkís, 2014)

This layout describes a single stage ORC cycle plant which has one open loop (left) and one closed loop (right). The open loop starts at the production well. The geothermal fluid circulates into a first heat exchanger where is used to heat the working fluid, commonly Isobutane or Isopentane. On the closed loop, the working fluid vaporizes and expands inside a turbine, producing electricity through a joint generator. After this step, the fluid is exhausted in an air cooled condenser, and pumped to a second heat exchanger where the geothermal fluid interacts one last time before being reinjected back to the reservoir. The process starts again at the boiler, competing the cycle.

8. EQUIPMENT COSTING

The costs for the equipment considered in this suitability study were estimated from methods found in literature. They may not represent the current market price for the equipment, but are only shown as a reference to an approximate price. For the direct-use of the geothermal resource, some of the equations and assumptions from Kiruja (2017), were considered. For the production of electricity with a binary cycle plant, equipment costs estimates from Verkís (2014), were used. Estimated costs for the field development were obtained from the CGS prefeasibility study´s final report.

A summary of the main costs of the equipment for energy supply to the geo-industrial park, based in scenarios presented in the previous sections, is shown in Table 14 y 15:

Scenario 1		
Section	Equipment	Cost estimate (USD)
Main pipeline	Pipeline	373 392
	Insulation	310 589
	Heat Exchanger	174 319
	Pumps	268 326
Return pipeline	Pipeline	157 934
	Pumps	105 764
Reinjection pipeline	Pipeline	520 645
	Pumps	--
Feasibility studies*, designs and permits		2’990 000
Total		4’900,969

*Appraisal well drilling operations to prove sufficient production.

Table 14: Main costs for Scenario 1

Scenario 2					
Temperature (ºC)	Generated power (kW)	Power plant (MUSD)	Steam Field (MUSD)	Hot Water Supply (MUSD)	Total (MUSD)
100	2500	8,6	37,9	4,9	51,4

Table 15: Main costs for Scenario 2

9. PROJECT PROFITABILITY

To evaluate the profitability of the project, scenario 2 was considered. This includes not only the energy savings from hot water supply but also from the generation of electricity. A discount rate of 8% per annum was assumed and a project lifetime of 30 years was selected. A summary of the variables used to calculate the Net Present Value (NPV) and Internal Rate of Return are shown in Table 16:

Profitability Assessment							
Reservoir Temperature (ºC)	Well depth (km)	Plant Capacity (kW)	Energy Price (USD/kWh)	Hot water price (USD/m^3)	Plant lifetime (Years)	Working cycle (days)	O&M Cost (% of income)
100	1,5	2500	0,12	2,39	30	340	0,1
Total Cash Inflows							
Total Capital Costs (MUSD)			Annual Income (MUSD)			O&M Costs (USD)	
51,4			5,9			0,59	

Table 16: Project profitability assessment

It was observed that the payback period of the project is between 8 and 10 years while the IRR is between 20 and 25% for the scenario 2. The Net Present Value was found to be 3,4 MUSD.

10. DISCUSSION

Although the preliminary results from the suitability to establish an industrial park with thermal energy from Chalpatán indicate a favorable scenario for the development of the project, the following aspects have to be considered:

- Feasibility studies are required to confirm the results obtained from the conceptual model. This include drilling two wells at a depth of approximately 1500 mt. to study the lithostratigraphy and the characteristics of the materials from the edge of the caldera, where a potential way to reach the aquifer exists; and to verify the presence of a water resource capable of transporting thermal energy to the surface in the form of hot water. (CGS, 2013)

- The profitability assessment has some limitations due that the price of certain commodities and the cost of the equipment can drastically change over time. Therefore, a sensitivity analysis is highly recommended once the feasibility studies provide definitive information on the resource´s thermal energy potential.
- The supply of non-geothermal water for the operation of the industrial park requires a high volume of this resource to be readily available. This has to be properly secured and monitored permanently to avoid its depletion or contamination due to an irresponsible use. A regulatory framework is needed in order to harmonize the legislation and to simplify the procedures of establishing and implementing the policies for boosting the direct use of the geothermal resources
- The geothermal resource will also need to be monitored permanently in order to maintain its sustainable status. A proper flow of geothermal brine will have to be reinjected in order to avoid subsidence in the ground and premature depletion of the field.
- A power plant was included as part of the suitability analysis. However, the investment required to reach the National Interconnected System was not included in this assessment and will have to be carefully determined beforehand. This can affect the profitability of the project.
- The role of the government in securing funding for the development of the project is crucial. It is also important that that feasibility studies are either carried on by public state company, or through international Institutions such as the World Bank, IMF or IADB.

11. CONCLUSION

The following conclusions can be drawn from the viability analysis made in this document:

1. The introduction of geothermal energy into the Ecuadorian productivity matrix has the potential to reduce the use of fossil fuels in the industry sector, as well as a reduction in greenhouse emissions.
2. The existence of a geothermal resource which is suitable for direct use and power generation.
3. The existence of potential industries in the province that can take advantage in terms of productivity and cost reduction, from the use of the geothermal resource located in Chalpatán.
4. The location of Chalpatán close to the source of industrial raw materials, a captive market for industrial goods, and a reliable source of energy, among others, makes it an ideal location for the development of an industrial park.
5. The project has payback period between 8 and 10 and a Net Present Value of 3,4 MUSD.

The Chalpatán geothermal field remains under the research scope of the National Institute for Geological and Energy Research - IIGE for possible future direct use purposes.

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